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Estimating the mass of the Milky Way using the rotation curve with Gaia DR3

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Abstract. We present a discussion of the Milky Way (MW) rotation curve in light of new Gaia data. These data suggest a Keplerian decline of the Galaxy's rotation curve from approximately 18 Kpc radial distance, implying a ∼ 20% decrease of the MW commonly accepted value of $\sim 10^{12} M_\odot$.

Resumo. Apresentamos uma discussão sobre a curva de rotação da Via Lactea (MW) à luz dos novos dados do Gaia. Estes dados sugerem um declínio Kepleriano na curva de rotação da Galáxia a partir de 18kpc de distância radial, implicando um decréscimo de 20% da massa massa dinâmica da Via Láctea estimada em geral em $\sim 10^{12} M_\odot$.

Keywords. Galaxy: kinematics and dynamics – Galaxy: structure – Galaxy: halo

1. Introduction

In the 1970s, it was observed that galaxies rotate at much higher speeds than expected by Kepler's second law Sofue & Rubin 2001. If only visible matter were present, the gravity generated would be insufficient to keep the stars in orbit. The presence of dark matter, with its additional mass, would explain these high rotation speeds. In this work, we aim to discuss the mass value of the Milky Way (MW) in light of the new data provided by the Gaia mission (DR3). The new data suggests a Keplerian decline in the Galaxy's rotation curve from approximately 18 kpc, a fact explored by several authors who suggest a significant decrease in the Milky Way's dynamic mass of up to 20% compared to the commonly accepted value of $\sim 10^{12} M_\odot$ Ou et al. 2024.

2. Methodology

The structure of a spiral galaxy may be separated into three components: Bulge, Disk, and Spherical Halo. Thus it is necessary to study the dynamics in each of these three components. It may also be important to consider the dynamics of gas and the contribution of the stellar halo but here we will restrict ourselves to the most significant components, the Bulge+Disc+Dark Matter Halo model. Since it was shown that the de Vaucouleurs model de Vaucouleurs 1948 did not fit the observed central rotation Graham 2013, an alternative was presented which is the exponential sphere model Sofue 2017 and Keeton 2014. This model describes the rotation velocity as a function of the volumetric mass density ρ as an exponential function of the radius r, with a scale parameter a, where the velocity is given by:

$$V^2(r) = \frac{GM^B(r)}{a}\left[\frac{1 - e^{-x}\left(1 + x + \frac{x^2}{2}\right)}{x}\right], \quad \text{where } x = \frac{r}{a}, \tag{1}$$

with $M^B(r) = \int_0^r 4\pi r'^2 \rho_B(r')dr'$ and $\rho_B(r) = \rho_B(0)\exp -(r/a)$.

As with the Bulge it is necessary to describe how the matter behaves along the disk. We can determine that the matter density of the disk also exhibits an exponential behavior Sofue 2017. For a thin exponential disk with density given by $\rho_D(r) = \rho_D(0)\exp -(r/b)$, where b is a scale factor determined for the disk, and $\rho_D(0)$ is the central density. The velocity is given by:

$$V^2(r) = \frac{2GM^D(r)}{b} x^2 \left(I_0(x)K_0(x) - I_1(x)K_1(x)\right), \tag{2}$$

where $x = \frac{r}{b}$, and I_i and K_i are Bessel functions for particular cases.

The most commonly used model for Spherical Dark Matter Halos is the NFW model (Navarro et al. 1996 and Navarro et al. 1997). The NFW profile is a function that describes how dark matter density varies with distance from the center of the halo. It is characterized by a density that increases smoothly as $\propto r^{-1}$ toward the center of the halo and then falls off smoothly as the distance from the center increases. The dark matter density $\rho^H(r)$ is given by:

$$\rho^H(r) = \frac{\rho^H_{(0)}}{\frac{r}{r_s}(1 + \frac{r}{r_s})^2}, \tag{3}$$

thus, the circular velocity of the halo as a function of the dark matter density of the NFW profile is given by:

$$V(r)^2 = G\frac{4\pi\rho^H_{(0)} r_s^3 \left(\frac{r}{r_s} - \ln\left(1 + \frac{r}{r_s}\right)\right)}{r}. \tag{4}$$

Notice that the presence of the NFW central cusp causes the rotation curve to rapidly rise at small radii ($V \propto r^{1/2}$ when $r \ll r_s$). For $r \gg r_s$ the dependence $\rho(r) \propto r^{-3}$ implies a slow decline of the rotation curve at large radii (see discussion in Keeton 2014).

3. Results

As it can be seen from Figure 1 below, the model described above provides good agreement with the observed circular velocity of the MW[1] up to 27 Kpc. Notice that Sofue's data extends up to 95 kpc and includes a variety of detection methods,

[1] Data were extracted from Sofue 2020

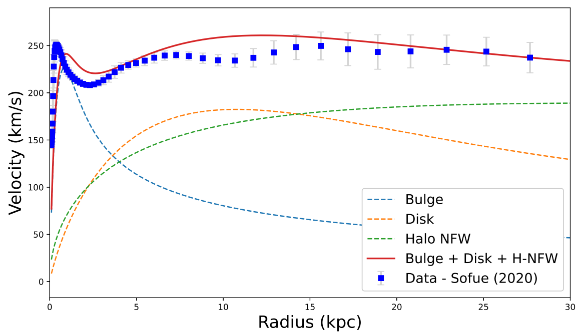

Figure 1. The observational data and MW rotation curve, together with their best fit model (data extracted from Sofue(2020).

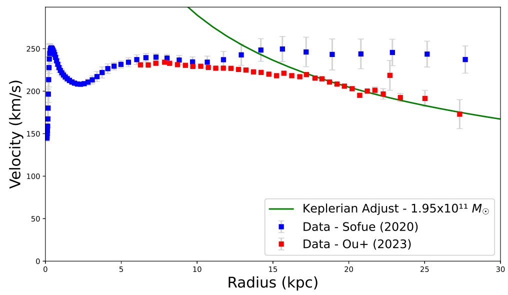

Figure 2. Comparison between the rotation curves from the data presented by Sofue (2020) (*blue*) and Ou *et al.* (2024) (*red*). The green line represents the Keplerian model presented by Jiao *et al.* (2023).

not only of bright objects (stars), but also including radial velocity measurements of neutral hydrogen (H I), carbon monoxide (CO), OB-type stars, red giant stars, globular clusters, and parallax and proper motion measurements (see more in Sofue2020). In the case of Gaia, the velocity measurements are limited to stars. For comparison purposes, we will restrict our analysis to the range from 0 to 30 kpc.

The GAIA third data release (DR3) showed a decline in the MW rotation curve between 15 and 30 kpc (see Fig 2) The most recent work discussing this subject is the paper by Jiao *et al.* (2023). In this paper the authors propose a Keplerian fit to the DR3 data, obtaining a new estimate for the mass of $1.95 \times 10^{11} M_\odot$. Below, we reproduce the fit from Jiao *et al.* (2023):

Using a χ^2 fit while fixing the mass of the disk and bulge, we were able to determine the best fit curve to this data. The best fit estimate to the dynamical mass was significantly reduced when compared to the previous model (Figure 3).

Using the equation of dynamical mass (obtained by equating the Gravitational Acceleration to the Centripetal Acceleration) we calculated the mass for each observational point, thereby obtaining a mass measurement for both the Sofue (2020) data and the new data. The Figure 4 below shows our results. Note that, for $R > 19$ kpc, the mass varies between $1.9 \times 10^{11} M_\odot$ and $2.0 \times 10^{11} M_\odot$, a result very similar to that presented by Jiao *et al.* (2023). In contrast, there is a decrease in the dynamical mass as compared to the data presented by Sofue (2020).

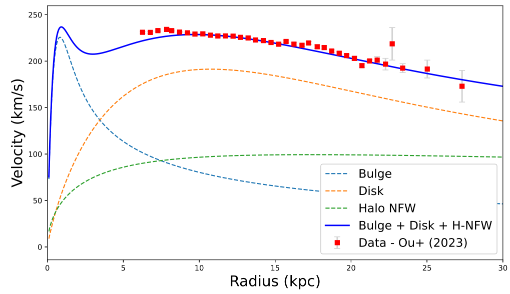

Figure 3. Rotation curve and observational data of the Milky Way. The blue curve represents the model with the mass adjustment for the new data. The χ^2 result for the mass of dark matter component $\sim 1.9 \times 10^{11} M_\odot$.

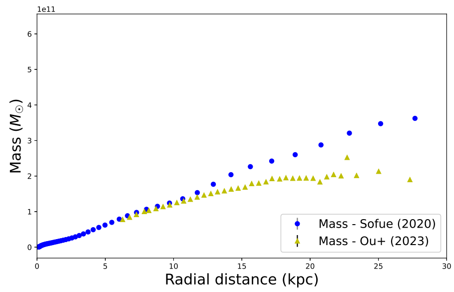

Figure 4. Graph of Mass as a function of radial distance.

4. Conclusions

Using a χ^2 fit for the mass parameters given by the profiles adopted for the Bulge, Disk, and Halo, we arrived at $\sim 3.210 \times 10^{11} M_\odot$ for the data presented in Sofue (2020). Applying the same fits to the data presented by Ou *et al.* (2024), we arrived at a mass estimate of $\sim 2.0410 \times 10^{11} M_\odot$. This result is very consistent with that presented by Jiao *et al.* (2023). However, such a change in the Milky Way's mass suggests that the dynamic mass should be of the order of $10^{11} M_\odot$ and not $10^{12} M_\odot$.

References

de Vaucouleurs, G. 1948, Annales d'Astrophysique, 11, 247
de Vaucouleurs, G. 1958, ApJ, 128, 465
Graham, A. 2013, BASI, 41, 61
Jiao, Y., et al. 2023, A&A, 678, A208
Keeton, C. 2014, *Principles of Astrophysics* (New York: Springer)
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Ou, X., et al. 2024, MNRAS, 528, 693
Sofue, Y., & Rubin, V. 2001, ARA&A, 39, 137
Sofue, Y. 2017, PASJ, 69, R1
Sofue, Y. 2020, Galaxies, 8, 37